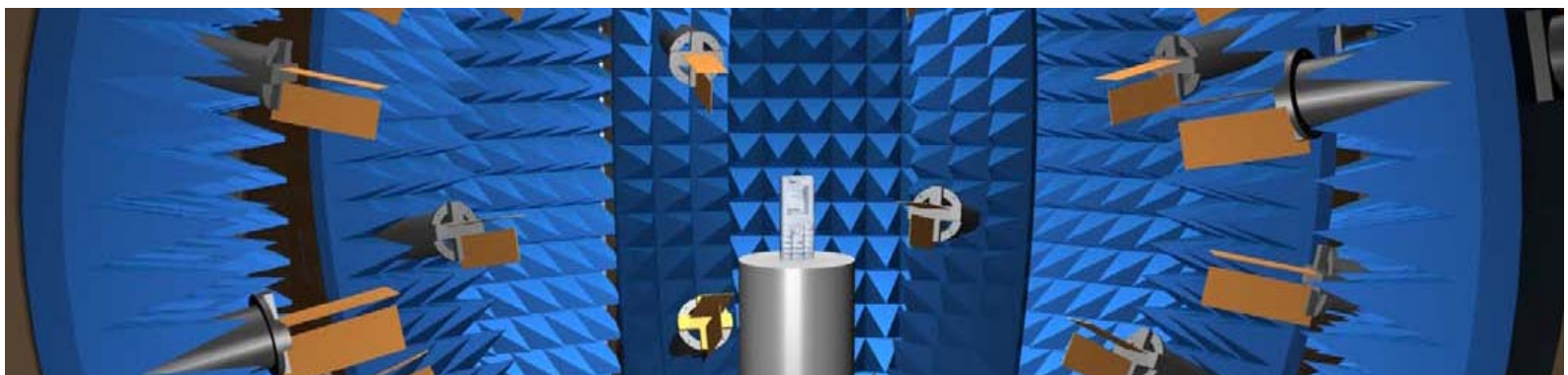


MEASUREMENT METHODS FOR MOBILE TERMINAL ANTENNA PERFORMANCE

Thesis for the degree of Doctor of Science in Technology

Juha Toivanen



Aalto University

School of Science and Technology

Faculty of Electronics, Communications, and Automation

Department of Radio Science and Engineering

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Dissertation for the degree of Doctor of Science in Technology to be presented with due permission of the Faculty of Electronics, Communications and Automation, for public examination and debate in Auditorium S 4 at Aalto University School of Science and Technology (Espoo, Finland) on the 24th of September, 2010, at 12 noon.

Distribution:

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ISBN 978-952-60-3310-5 (paper)

ISBN 978-952-60-3311-2 (electronic)

ISSN 1797-4364 (paper)

ISSN 1797-8467 (electronic)

Picaset Oy

Helsinki 2010

ABSTRACT OF DOCTORAL DISSERTATION		AALTO UNIVERSITY SCHOOL OF SCIENCE AND TECHNOLOGY P.O. BOX 13000, FI-00076 Aalto http://www.tkk.fi	
Author Juha Toivanen			
Name of the dissertation Measurement methods for mobile terminal antenna performance			
Manuscript submitted 30 May, 2010		Manuscript revised 13 August, 2010	
Date of the defence 24 September, 2010			
<input type="checkbox"/> Monograph		<input checked="" type="checkbox"/> Article dissertation (summary + original articles)	
Faculty	Electronics, Communications and Automation		
Department	Radio Science and Engineering		
Field of research	Radio Engineering, Electromagnetics		
Opponent(s)	PhD Philip Miller (National Physical Laboratory, UK), DSc (Tech) Jussi Rahola (Optenni Oy)		
Supervisor	Professor (pro tem) Tommi Laitinen		
Instructor	Professor (pro tem) Tommi Laitinen		
<p>Abstract</p> <p>Mobile terminal antennas and antenna systems are central in the development of spectrum-efficient high-data-rate mobile communications systems. Among the things that influence the link performance are the antenna radiation characteristics, the effect of the human body, and the propagation environment in which the antenna operates. Traditional antenna measurement methods are expensive and time consuming, requiring large anechoic facilities. Their advantage is the high achievable measurement accuracy, but measurements with test persons are very difficult because of the long measurement times. Furthermore, measurements of the effect of the propagation channel on the performance of the antenna system are not possible. The last two effects are very important in mobile terminal antenna testing, whereas extreme accuracy is often not required. Therefore, development of new testing methods is needed for mobile terminal antenna performance evaluation.</p> <p>This thesis deals with the following topics related to antenna performance evaluation: reduction of the measurement time and costs of antenna pattern measurements, effect of the human body on the antenna performance, and over-the-air testing of antennas in realistic propagation environments. A method is developed and experimentally verified that enables antenna pattern measurements in environments that have high reflectivity levels. This reduces the testing costs because radio wave absorbers are not required in the testing. This method is also presented as a way to facilitate the calibration of a multi-probe antenna measurement system. A novel type of a multi-probe system is reported and improvements upon it are implemented that allow a considerable reduction of test times. Using this system, antenna performance measurements with live test persons are carried out and the variation of the results between different people (and its cause) is shown. Finally, a technique is presented for synthesizing arbitrary multi-path propagation environments in laboratory conditions, using multi-probe configurations. This enables repeatable testing of mobile terminals in realistic operating conditions without the need to perform field measurements.</p>			
Keywords Antenna measurements, mobile terminal, field compensation, user effect, body loss, OTA testing, MIMO, radio channel, field synthesis			
ISBN (printed) 978-952-60-3310-5		ISSN (printed) 1797-4364	
ISBN (pdf) 978-952-60-3311-2		ISSN (pdf) 1797-8467	
Language English		Number of pages 76 + 45	
Publisher Aalto University, Department of Radio Science and Engineering			
Print distribution Aalto University, Department of Radio Science and Engineering			
<input checked="" type="checkbox"/> The dissertation can be read at http://lib.tkk.fi/Diss/2010/isbn9789526033112/			

VÄITÖSKIRJAN TIIVISTELMÄ		AALTO-YLIOPISTON TEKNILLINEN KORKEAKOULU PL 13000, 00076 Aalto http://www.tkk.fi	
Tekijä Juha Toivanen			
Väitöskirjan nimi Matkaviestinpäätelaitteiden antennisuorituskyvyn mittaamenetelmiä			
Käsi kirjoituksen päivämäärä	30.5.2010	Korjatun käsi kirjoituksen päivämäärä	13.8.2010
Väitöstilaisuuden ajankohta 24.9.2010			
<input type="checkbox"/> Monografia		<input checked="" type="checkbox"/> Yhdistelmäväitöskirja (yhteenvedo + erillisartikkelit)	
Tiedekunta	Elektroniikan, tietoliikenteen ja automaation tiedekunta		
Laitos	Radiotieteen ja -tekniikan laitos		
Tutkimusala	Radiotekniikka, sähkömagnetiikka		
Vastaväittäjä(t)	PhD Philip Miller (National Physical Laboratory, UK), TkT Jussi Rahola (Optenni Oy)		
Työn valvoja	Professori (pro tem) Tommi Laitinen		
Työn ohjaaja	Professori (pro tem) Tommi Laitinen		
Tiivistelmä <p>Matkaviestinpäätelaitteiden antennijärjestelmät ovat keskeisessä roolissa uusien spektritehokkaiden matkaviestinjärjestelmien kehityksessä. Radioyhteyden laatuun vaikuttavia asioita ovat mm. antennin säteilyominaisuudet, käyttäjän vaikutus, sekä radiotieympäristö, jossa antenni toimii. Perinteiset antennimittausmenetelmät, joissa käytetään suuria radiokaiuttomia tiloja, ovat kalliita ja aikaavieviä. Näillä menetelmillä on mahdollista päästä suureen mittaustarkkuuteen, mutta pitkän mittausajan vuoksi mittaukset koehenkilöiden kanssa ovat epäkäytännöllisiä. Myöskään radiotieympäristön vaikutusta antennijärjestelmän suorituskykyyn ei ole mahdollista mitata. Käyttäjän ja radiokanavan vaikutus antennijärjestelmän suorituskykyyn on kuitenkin erittäin suuri ja siten myös näiden vaikutusten testaaminen on tärkeää, kun taas hyvin suurta mittaustarkkuutta ei välttämättä vaadita. Näin ollen tarvitaan uusia mittaamenetelmiä matkaviestinpäätelaitteiden antennijärjestelmien suorituskyvyn arviointiin.</p> <p>Tässä työssä käsitellään seuraavia antennisuorituskyvyn arviointiin liittyviä asioita: antennin säteilyominaisuuksien mittausajan ja -kulujen vähentäminen, käyttäjän vaikutus antennin suorituskykyyn, ja antennien testaaminen realistisissa radiotieympäristöissä. Työssä on kehitetty antennimittausmenetelmä, joka mahdollistaa mittaukset heijastavissa ympäristöissä. Tällöin mittaus tilassa ei välttämättä tarvita absorbaattoreita, mikä vähentää kustannuksia. Työssä myös osoitetaan, että samaa menetelmää voidaan soveltaa ns. moniantennimittausjärjestelmien kalibrointiin. Lisäksi työssä on edelleen kehitetty uudentyyppistä moniantennimittausjärjestelmää, joka mahdollistaa huomattavan lyhyet mittausajat, ja arvioitu tämän järjestelmän suorituskykyä. Tätä järjestelmää käyttäen on tutkittu käyttäjän vaikutusta matkapuhelinantennin suorituskykyyn ja osoitettu, mistä suuri mittausarvojen vaihtelu eri käyttäjien välillä johtuu. Työssä esitetään myös menetelmä mielivaltaisten radiotieympäristöjen luomiseen laboratorioolosuhteissa. Tämä mahdollistaa sen, että radiokanavan vaikutus antennisuorituskykyyn voidaan mitata kontrolloiduissa, toistettavissa olosuhteissa.</p>			
Asiasanat Antennimittaukset, matkapuhelin, kenttäkompensatio, käyttäjän vaikutus, kehohäviöt, OTA-testaus, MIMO, radiokanava, kenttäsynteesi			
ISBN (painettu)	978-952-60-3310-5	ISSN (painettu)	1797-4364
ISBN (pdf)	978-952-60-3311-2	ISSN (pdf)	1797-8467
Kieli	englanti	Sivumäärä	76 + 45
Julkaisija Aalto-yliopisto, Radiotieteen ja -tekniikan laitos			
Painetun väitöskirjan jakelu Aalto-yliopisto, Radiotieteen ja -tekniikan laitos			
<input checked="" type="checkbox"/> Luettavissa verkossa osoitteessa http://lib.tkk.fi/Diss/2010/isbn9789526033112/			

Preface

This thesis work has been carried out in the Department of Radio Science and Engineering of the Aalto University in the years 2004-2005 and 2008-2010. I would like to extend my warmest thanks to Professor Pertti Vainikainen for supervising this thesis work and to Professor (pro tem) Tommi Laitinen for instructing me throughout this work and for also acting as the supervisor in the final stages of the work. Your expertise has been of great help to me, and I have learned a lot from both of you ever since I first started in the Radio Laboratory as a summer trainee back in 2001.

The pre-examiners Professor Edward B. Joy and Professor Buon Kiong Lau deserve my gratitude for their insightful comments and suggestions on how to improve the thesis.

I want to thank my current and former colleagues who have greatly helped me in my research and thus contributed to making the thesis better. Dr. Clemens Icheln, Dr. Sergey Pivnenko, Joonas Krogerus, Dr. Veli-Matti Kolmonen, Lasse Nyberg, Viktor Sibakov, Eino Kahra, and many others, it has been a pleasure working with you.

I especially wish to thank Dr. Pekka Ikonen, whose suggestion on funding opportunities ultimately brought me back from the industry to finish this thesis, and Timo Hakala, my former supervisor in the industry, who was very positive and encouraging about me undertaking this project.

For financial support, I thank the Academy of Finland, the Finnish Foundation for Economic and Technology Sciences, the Finnish Society of Electronics Engineers, the HPY Research Foundation, the Walter Ahlström Foundation, the Ella and Georg Ehrnrooth Foundation, the Ulla Tuominen Foundation, and the Aalto University.

Finally, I want to thank my family for all their help and support. I am glad you can share this achievement with me.

Espoo, 1 September 2010

Juha Toivanen

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List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

- I** J. T. Toivanen, T. A. Laitinen, and P. Vainikainen, "Modified test zone field compensation for small-antenna measurements," accepted for publication in *IEEE Trans. Antennas and Propagation*.
- II** J. T. Toivanen, T. A. Laitinen, S. Pivnenko, and L. Nyberg, "Calibration of multi-probe antenna measurement system using test zone field compensation," in *Proc. 3rd European Conference on Antennas and Propagation (EuCAP'09)*, Berlin, Germany, Mar. 2009, pp. 2916–2920.
- III** T. A. Laitinen, J. Toivanen, C. Icheln, and P. Vainikainen, "Spherical measurement system for determination of complex radiation patterns of mobile terminals," *Electronics Letters*, vol. 40, no. 22, pp. 1392–1394, Oct. 2004.
- IV** J. Toivanen, T. A. Laitinen, C. Icheln, and P. Vainikainen, "Spherical wideband measurement system for mobile terminal antennas," in *Proc. 2nd IASTED International Conference on Antennas, Radar and Wave Propagation*, Banff, Alberta, Canada, July 2005, pp. 360–365.
- V** J. Krogerus, J. Toivanen, C. Icheln, and P. Vainikainen, "Effect of the human body on total radiated power and 3-D radiation pattern of mobile handsets," *IEEE Trans. Instrumentation and Measurement*, vol. 56, no. 6, pp. 1392–1394, Dec. 2007.
- VI** J. T. Toivanen, T. A. Laitinen, V.-M. Kolmonen, and P. Vainikainen, "Reproduction of arbitrary multi-path environments in laboratory conditions," accepted for publication in *IEEE Trans. Instrumentation and Measurement*.

Author's contribution

The author has the main contribution to all the publications where he is listed as the first author ([I], [II], [IV], [VI]). The author has a significant contribution to the other publications ([III], [V]).

The author invented the method presented in publication [I]. He carried out all the theoretical formulations and performed the simulations. He also planned and performed the measurements with the single-probe system, and participated in and instructed the reference measurements and the measurements with the multi-probe system. He wrote all the software codes and carried out the measurement data analysis.

The author invented the calibration method presented in publication [II]. He planned, participated in, and instructed the measurements, and performed the measurement data analysis.

The author participated in the planning of the measurements in publication [III]. He implemented the measurement system control software and participated in the system calibration. He mostly carried out the measurements and measurement data analysis, partly using software codes by T. Laitinen.

The author had the main responsibility for publication [IV]. He planned and implemented most of the system hardware and software development, and carried out the measurements and measurement data analysis.

In publication [V], the author participated in the planning and had the main responsibility for executing the test person measurements with the multi-probe system. He partly carried out the measurement data analysis.

The author developed the synthesis method presented in publication [VI]. He wrote all the software codes and performed all the simulations and analyses.

List of Abbreviations

2-D	Two-Dimensional
3-D	Three-Dimensional
3GPP	3 rd Generation Partnership Project
APC	Antenna Pattern Comparison
BER	Bit Error Rate
BL	Body Loss
CATR	Compact Antenna Test Range
CINR	Carrier-to-Interference-and-Noise Ratio
COST	European Cooperation in Science and Technology
CW	Continuous Wave
DoA	Direction of Arrival
DoD	Direction of Departure
DUT	Device Under Test
EPIC	Extended Probe Instrument Calibration
FFT	Fast Fourier Transform
GSM	Global System for Mobile Communications
IEEE	Institute of Electrical and Electronics Engineers
IMT	International Mobile Telecommunications
IST	Information Society Technologies
LOS	Line Of Sight
MEG	Mean Effective Gain
MIMO	Multiple-Input Multiple-Output
OTA	Over-The-Air
PC	Personal Computer
RSSI	Received Signal Strength Indicator
SCM	Spatial Channel Model
SFE	Spatial Fading Emulator
SNR	Signal-to-Noise Ratio
TIS	Total Isotropic Sensitivity
TRP	Total Radiated Power
TZF	Test Zone Field
VNA	Vector Network Analyzer
WINNER	Wireless World Initiative New Radio
XPR	Cross-polarization Power Ratio

List of Symbols

a_{smn}	amplitude of the incoming spherical waves
$a(\mu, n, -\mu, v, p)$	linearization coefficient
c	index for the radial dependence of the spherical wave functions
$d_{m\mu}^n(\theta)$	spherical-wave rotation coefficients
i, j	indices
j	imaginary unit
k	wave number
r	radius
r_0	radius of the DUT or test zone minimum sphere
s, m, n	spherical mode indices
t	time
v	antenna input signal
v_p	probe input signal
w	received signal
$z_n^{(c)}$	function for the radial dependence of the spherical waves
C	channel capacity
$C_{s\mu m}^{\sigma v(3)}(kr)$	spherical-wave translation coefficients
D	antenna cross-section dimension
\bar{E}	vectorial electric field
$\bar{F}_{smn}^{(3)}$	outgoing spherical wave functions
$G(\theta, \varphi)$	antenna power gain pattern
\mathbf{H}	channel matrix
\mathbf{I}	identity matrix
J	number of spherical modes
M	number of measurement points
N	truncation number for the spherical mode series
N_r	number of receive antennas
N_t	number of transmit antennas
$P(\theta, \varphi)$	angular power distribution of incoming waves
$\bar{P}_n^{ m }$	normalized associated Legendre functions
R_{smn}	antenna receiving coefficients
S_{ij}	scattering parameters
T_{smn}	antenna transmission coefficients
$T_{\sigma\mu\nu}^p$	probe transmission coefficients
λ	wavelength
θ	elevation angle in the spherical coordinate system
φ	azimuth angle in the spherical coordinate system
χ	roll angle
ψ	polarization
η	wave admittance

σ, μ, ν	spherical mode indices, probe coordinate system
ρ_e	envelope correlation coefficient
ρ_c	complex correlation coefficient
ω	angular frequency
$()^H$	Hermitian transpose
$()^*$	conjugate
$()^\dagger$	pseudo-inverse

1 Introduction

Mobile communications systems have become an integral part of the modern society. Improved performance and higher data rates are required of these systems to accommodate for various emerging applications. In a mobile communications link, the antenna is the means to couple the signal to the intermediary space between the two ends of the link. It is important to understand the effects that play a role in this coupling to be able to optimize the antenna design and thus improve the performance of the communications link. This is where antenna measurements come into the picture.

In this thesis, new measurement methods are developed that facilitate different aspects of mobile terminal antenna testing. Among the things that influence the link performance in a mobile communications system are the antenna radiation characteristics, the effect of the human body, and the propagation environment in which the antenna operates. Traditional single-probe antenna measurement methods that require large anechoic facilities are expensive and time consuming. Their advantage is the high achievable measurement accuracy, but measurements with test persons are very difficult because of the long measurement times. Furthermore, measurements of the effect of the radio propagation channel on the performance of the antenna are not possible. The last two effects are very important in connection with mobile terminal antenna testing, whereas extreme accuracy is often not required. Therefore, development of new testing methods is needed for mobile terminal antenna performance evaluation. Although the focus in this work is on mobile terminal antennas, the results (especially on the measurement of the radiation characteristics) are applicable for other small antennas, as well.

The general structure of the thesis is as follows. The first chapters deal with basic antenna measurement parameters and their determination by single- and multi-probe measurement systems. After this, the focus shifts to the measurement of the effect the user has on the mobile terminal radio performance (for single-antenna devices). Finally, new testing challenges posed by multi-antenna terminals are investigated. A more detailed description of the contents of the chapters is given in the following.

Chapter 2 gives a short introduction to the theoretical background of spherical near-field antenna measurements, which is extensively applied in this thesis. The spherical-wave expansion, the probe correction, and the solution methods for the spherical-wave transmission formula are discussed.

Chapter 3 discusses the measurement of basic antenna parameters like the radiation pattern and the efficiency, using single-probe antenna measurement systems. A method is developed and experimentally verified that enables antenna pattern measurements in environments that have high reflectivity levels. It is based on compensation of the effect

of reflections in the measurement environment through a calibration measurement of the environment with a known reference antenna. This reduces the testing costs because measurements can be performed, for example, in a normal laboratory room without the requirement for expensive anechoic facilities.

Chapter 4 focuses on multi-probe antenna measurement systems. A novel type of a multi-probe system is reported and improvements upon it are implemented that allow a considerable reduction of test times. Furthermore, it is shown how the reflection compensation method presented in Chapter 3 can be adapted for facilitating the calibration of a multi-probe system. This new method can be used to calibrate the system for the channel response differences and also for the signal reflections between the probe antennas.

In Chapter 5, the effect of the human body on the performance of the mobile terminal antenna is investigated. The proximity of the body typically has a large influence on the radiation of the antenna. Antenna performance measurements with real test persons have been carried out using the multi-probe measurement system presented in Chapter 4. The results of these measurements are reported and they provide insight into the effect of the human body and the variation of antenna performance parameters with different people.

In Chapter 6, the influence of the radio propagation environment on the antenna performance is discussed. There can be large differences in the performance of different antenna configurations, depending on the type of the radio channel environment, in which they operate. This is because emerging wireless communications systems employ multi-antenna configurations that dynamically change their radiation characteristics in response to the changing radio channel environment in order to optimize the link performance. A technique is presented for synthesizing arbitrary multi-path propagation environments in laboratory conditions with the use of multi-probe configurations. This enables repeatable over-the-air (OTA) testing of mobile terminals in realistic operating conditions without the need to perform field measurements, which reduces the time and costs of the tests.

Finally, summary of the publications constituting this thesis is presented in Chapter 7 and conclusions are given in Chapter 8.

2 Spherical near-field measurement theory

The results of this thesis are largely based on the spherical-wave theory, as applied to spherical near-field antenna measurements. Therefore, a review of the relevant theoretical concepts is given in this chapter. Section 2.1 introduces the spherical-wave expansion; Section 2.2 discusses the spherical-wave transmission formula, which gives the signal transmitted between two antennas; and Section 2.3 presents the solution method applied in this thesis to solve the radiation characteristics of the device under test (DUT) from spherical near-field measurements.

2.1 Expansion

The spherical-wave expansion has been long known and used in the context of radiation problems [1] [2]. The spherical wave functions form an orthonormal set that provides a complete solution to Maxwell's equations in free space. Therefore, any electromagnetic field radiated by the DUT can be expressed as a properly weighted sum of the spherical wave functions. An extensive treatment of the spherical-wave theory applied to antenna measurements is given in [3], and in this thesis, the definitions and normalizations adopted in [3] are used. The time dependence $e^{j\omega t}$ is assumed for the electromagnetic fields. The expansion for the electric fields radiated by an antenna structure is of the form

$$\bar{E}(r, \theta, \varphi) = \frac{k}{\sqrt{\eta}} \sum_{s=1}^2 \sum_{n=1}^{\infty} \sum_{m=-n}^n v T_{smn} \bar{F}_{smn}^{(3)}(r, \theta, \varphi), \quad (2.1)$$

where $\bar{E}(r, \theta, \varphi)$ is the electric field value in a position given by the spherical coordinates r , θ , and φ ; k is the wave number; η is the wave admittance; s , m , and n are the spherical mode indices; v is the input signal; T_{smn} are the spherical transmission coefficients of the antenna; and $\bar{F}_{smn}^{(3)}(r, \theta, \varphi)$ are the outgoing spherical vector wave functions. The spherical vector wave functions are here defined as

$$\begin{aligned} \bar{F}_{lmn}^{(c)}(r, \theta, \varphi) = & \frac{1}{\sqrt{2\pi}} \frac{1}{\sqrt{n(n+1)}} \left(-\frac{m}{|m|} \right)^m \\ & \cdot \left\{ z_n^{(c)}(kr) \frac{im\bar{P}_n^{|m|}(\cos\theta)}{\sin\theta} e^{im\varphi} \hat{\theta} - z_n^{(c)}(kr) \frac{d\bar{P}_n^{|m|}(\cos\theta)}{d\theta} e^{im\varphi} \hat{\phi} \right\} \end{aligned} \quad (2.2)$$

and

$$\bar{F}_{2mn}^{(c)}(r, \theta, \varphi) = \frac{1}{\sqrt{2\pi}} \frac{1}{\sqrt{n(n+1)}} \left(-\frac{m}{|m|} \right)^m \left\{ \begin{aligned} & \frac{n(n+1)}{kr} z_n^{(c)}(kr) \bar{P}_n^{|m|}(\cos \theta) e^{im\varphi} \hat{r} + \frac{1}{kr} \frac{d}{d(kr)} \{ kr z_n^{(c)}(kr) \} \frac{d\bar{P}_n^{|m|}(\cos \theta)}{d\theta} e^{im\varphi} \hat{\theta} \\ & + \frac{1}{kr} \frac{d}{d(kr)} \{ kr z_n^{(c)}(kr) \} \frac{im\bar{P}_n^{|m|}(\cos \theta)}{\sin \theta} e^{im\varphi} \hat{\phi} \end{aligned} \right\} \quad (2.3)$$

In the equations above, $\bar{P}_n^{|m|}$ are the normalized associated Legendre functions and the radial function $z_n^{(c)}$ (of order n) is one of the following:

- $c = 1$ spherical Bessel function of the first kind
- $c = 2$ spherical Bessel function of the second kind
- $c = 3$ spherical Hankel function of the first kind
- $c = 4$ spherical Hankel function of the second kind

$c = 1$ and $c = 2$ correspond to radial standing waves, finite and infinite at the origin, respectively. $c = 3$ and $c = 4$ correspond to radial outgoing and incoming waves, respectively. The radiation characteristics of the DUT are determined completely by the T_{smn} and in the spherical near-field technique they are found by determining $\bar{E}(r, \theta, \varphi)$ at known positions and solving Eq. (2.1) for the T_{smn} .

In expansion (2.1), index n goes from 1 to infinity. For the solution to be feasible in practice, the expansion must be truncated to a finite length by assigning a truncation number N to index n . With the radius of the minimum sphere enclosing the DUT designated as r_0 , the well-known truncation rule is [3]

$$N = \lfloor kr_0 \rfloor + n_1, \quad (2.4)$$

where $\lfloor \cdot \rfloor$ is the integer floor operator and n_1 is a number determined by the desired accuracy. Typically, small values for n_1 (e.g. $n_1 = 0$ or $n_1 = 1$) are sufficient for electrically small antennas and/or in applications where very high accuracy is not required [4]-[7] and $n_1 = 10$ is considered sufficient for most practical applications [3].

2.2 Probe correction

A further complication is that $\bar{E}(r, \theta, \varphi)$ cannot be measured directly, except by an ideal Hertzian dipole. This means that the probe characteristics influence the measured signal, and probe correction must be applied in order to improve the accuracy of the measurement result. For later purposes, the probe correction will be discussed here for the case where the probe is in the transmitting mode and the DUT in the receiving mode. The probe characteristics must be known and are defined by the transmission coefficients $T_{\sigma\mu\nu}^p$. The radiation of the probe produces incoming spherical waves in the DUT coordinate system, whose amplitudes a_{smn} can be calculated as

$$a_{smn} = \frac{v_p}{2} \sum_{\sigma\mu\nu} T_{\sigma\mu\nu}^p C_{s\mu n}^{\sigma\nu(3)}(-kr) e^{-i\mu\chi} d_{m\mu}^n(-\theta) e^{-im\varphi}. \quad (2.5)$$

In this formula, the location of the probe in the DUT coordinate system is given by the distance r and the Euler angles θ , φ , and χ ; v_p is the probe input signal; the spherical mode indices s , m , and n refer to the DUT coordinate system and the indices σ , μ , and ν refer to the probe coordinate system; $C_{s\mu n}^{\sigma\nu(3)}(kr)$ are the spherical-wave translation coefficients, defined as (Appendix 3 in [3])

$$C_{\sigma\mu\nu}^{sn(c)}(kr) = \sqrt{\frac{(2n+1)(2\nu+1)}{n(n+1)\nu(\nu+1)}} \sqrt{\frac{(\nu+\mu)!(n-\mu)!}{(\nu-\mu)!(n+\mu)!}} (-1)^\mu \frac{1}{2} i^{n-\nu} \sum_{p=|n-\nu|}^{n+\nu} \left[i^{-p} \left(\delta_{s\sigma} \{n(n+1) + \nu(\nu+1) - p(p+1)\} + \delta_{3-s,\sigma} \{2i\mu kr\} \right) a(\mu, n, -\mu, \nu, p) z_p^{(c)}(kr) \right] \quad (2.6)$$

Recursion formulas for efficient calculation of the linearization coefficient $a(\mu, n, -\mu, \nu, p)$ are presented in [8]. In Eq. (2.5), the translation coefficient has a negative argument. It can be calculated by using the symmetry relation

$$C_{s\mu n}^{\sigma\nu(c)}(-kr) = C_{\sigma, -\mu, \nu}^{sn(c)}(kr). \quad (2.7)$$

The spherical-wave rotation coefficients $d_{m\mu}^n(\theta)$ are defined as (Appendix 2 in [3])

$$d_{\mu m}^n(\theta) = \sqrt{\frac{(n+\mu)!(n-\mu)!}{(n+m)!(n-m)!}} \sum_{\sigma} \binom{n+m}{n-\mu-\sigma} \binom{n-m}{\sigma} (-1)^{n-\mu-\sigma} \left(\cos \frac{\theta}{2}\right)^{2\sigma+\mu+m} \left(\sin \frac{\theta}{2}\right)^{2n-2\sigma-\mu-m} \quad (2.8)$$

where the binomial coefficient is given by

$$\binom{i}{j} = \frac{i!}{(i-j)!j!} \quad (2.9)$$

and the summation over σ is carried out involving all terms except those that result in negative arguments for the factorials.

Then, the signal w received by the DUT is given as (Eq. (3.13) in [3])

$$w = \sum_{smn} R_{smn} a_{smn}, \quad (2.10)$$

where R_{smn} represents the unknown DUT receiving coefficients. Combining Eqs. (2.5) and (2.10) gives the spherical-wave transmission formula

$$w(r, \theta, \varphi, \chi) = \frac{v_p}{2} \sum_{\substack{\sigma\mu\nu \\ smn}} T_{\sigma\mu\nu}^p C_{s\mu n}^{\sigma\nu(3)}(-kr) e^{-i\mu\chi} d_{m\mu}^n(-\theta) e^{-im\varphi} R_{smn}. \quad (2.11)$$

By measuring the signal received by the DUT for different relative probe locations, this formula can be solved for the R_{smn} of the DUT, which entails the radiation characteristics of the DUT are found using Eq. (2.1) and the relation

$$T_{smn}(\varphi, \theta, \chi) = (-1)^m R_{s, -m, n}(\varphi, \theta, \chi), \quad (2.12)$$

which is valid for reciprocal antennas. The discrete solution methods are discussed in the next section.

2.3 Solution methods

Generally, two different solution methods for solving Eq. (2.11) for the R_{smn} are used [9]. The first method exploits the orthogonalities of the spherical-wave rotation functions and is computationally efficient because the Fast Fourier Transform (FFT) technique can be applied in the calculations (Section 4.3 in [3]). The second method involves solving a system of linear equations through inverse-matrix techniques and is computationally more demanding. Therefore, it is feasible mostly for electrically small antennas, where the number of terms in the expansions is not very large. Since this is usually the case with mobile terminal antennas of typical size, this method is applied in this thesis and will be presented in the following.

By measuring the signal received by the DUT for different relative probe locations (determined by r, φ, θ , and χ), one can construct the following matrix equation using Eq. (2.10).

$$\begin{bmatrix} a_1(r_1, \varphi_1, \theta_1, \chi_1) & \dots & a_J(r_1, \varphi_1, \theta_1, \chi_1) \\ a_1(r_2, \varphi_2, \theta_2, \chi_2) & \dots & a_J(r_2, \varphi_2, \theta_2, \chi_2) \\ \vdots & \vdots & \vdots \\ a_1(r_M, \varphi_M, \theta_M, \chi_M) & \dots & a_J(r_M, \varphi_M, \theta_M, \chi_M) \end{bmatrix} \begin{bmatrix} R_1 \\ \vdots \\ R_J \end{bmatrix} = \begin{bmatrix} w_1 \\ \vdots \\ w_M \end{bmatrix} \quad (2.13)$$

Using matrix notation, the above equation is written as $\mathbf{A}\mathbf{r} = \mathbf{w}$. Note that a single-index notation has been adopted for the spherical modes, i.e., $a_{smn} \rightarrow a_j$ such that $j = 2\{n(n+1) + m - 1\} + s$ and j goes from 1 to J . The matrix \mathbf{A} is an M -by- J matrix such that each row corresponds to a different measurement point and M is the total number of measurement points; J is the required number of spherical modes, determined by the size of the DUT, applying the truncation rule (2.4); \mathbf{r} is a column vector containing the receiving coefficients R_{smn} of the DUT and \mathbf{w} is a column vector containing the measured signal values. $M \geq J$ is required so that there are more measurement values than unknowns in the equation. The solution is obtained by using the Moore-Penrose pseudoinverse [10]

$$\mathbf{r} = \mathbf{A}^\dagger \mathbf{w} = (\mathbf{A}^H \mathbf{A})^{-1} \mathbf{A}^H \mathbf{w}. \quad (2.14)$$

3 Measurement of antenna radiation characteristics: single-probe systems

Single-probe antenna measurement systems installed in outdoor ranges or anechoic chambers have traditionally been the most common way of measuring antenna radiation characteristics. Despite the emergence of multi-probe measurement systems, single-probe systems are still widely used also in mobile terminal antenna testing and have their own advantages. This chapter presents an overview of single-probe measurements, focusing on the measurement of electrically small antennas.

First, in Section 3.1 the typical parameters of interest used in mobile terminal antenna testing are discussed. In Section 3.2, some common measurement system configurations and measurement techniques are described. Section 3.3 presents an overview of methods for compensating the deleterious effect of signal reflections in the measurement chamber. These methods are applied in order to improve the accuracy of the measurement results. Finally, Section 3.4 summarizes the contributions of this thesis with respect to antenna measurements using single-probe systems.

3.1 Parameters of interest

The figures of merit discussed in this section are primarily used in the measurement of mobile terminals utilizing a single antenna element. Tests of advanced multi-antenna systems require different figures of merit, and are discussed in Section 6.1.

3.1.1 Radiation pattern

The radiation pattern of an antenna presents some aspect of radiation (e.g. intensity, phase etc.) as a function of direction relative to the antenna. It describes how the antenna radiates to (or receives radiation from) different directions. In the case of mobile terminal antennas, a typical parameter plotted as a radiation pattern is the directivity, which gives the normalized power density radiated by the antenna to different directions. An example of a measured radiation pattern of a dipole antenna is shown in Fig. 1, where the total field amplitude radiated by the antenna is plotted as a function of the elevation angle.

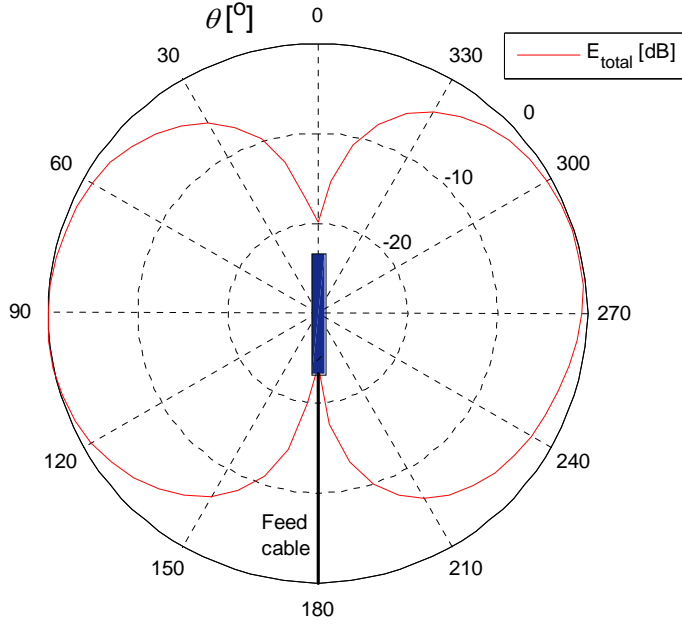


Fig. 1. Radiation pattern of a sleeve dipole antenna shows the total radiated field amplitude (normalized to 0 dB) as a function of direction relative to the antenna.

3.1.2 Total radiated power

The total radiated power (TRP) is, as the term suggests, the total power radiated by the antenna. It is obtained by integrating the radiation pattern over the whole 4π solid angle [11]. With mobile terminals, the maximum allowed TRP is usually defined by the regulatory authorities. In a realistic usage situation, the body of the user affects the amount of radiated power both by changing the input impedance of the mobile terminal antenna and by absorbing power in the tissues.

The TRP is an absolute quantity, which depends not only on the losses in the antenna structure but also on the input power fed to the antenna. Therefore, to obtain a measurement of the losses in the antenna structure (the efficiency of the antenna) the measured TRP can be compared to the TRP of a reference antenna with a known efficiency, using the same input power level in both measurements. The differences in input matching must be compensated for, so that the power accepted by both antennas is the same. Otherwise, the obtained efficiency is the so-called total efficiency, which includes the mismatch loss.

With active mobile terminals, i.e., fully functional mobile terminals operating in the battery mode with their internal transceivers, the actual power level fed to the antenna, or the power reflected from the antenna due to mismatch cannot typically be known, at least not accurately. In this case, one can obtain an efficiency measure by setting the terminal to transmit at full power and comparing the measured TRP to the maximum allowed TRP, which, e.g., in the case of handheld GSM900 terminals is 33 dBm [12]. This efficiency measure can be called the realized total efficiency, and it tells how the terminal operates with respect to the regulatory power constraint.

3.1.3 Total isotropic sensitivity

The total isotropic sensitivity (TIS) is a figure of merit measured for active mobile terminals. The measurement procedure is similar to that of the TRP [11]. First, the sensitivity pattern is measured by finding the power level at which the quality of the received signal, indicated, e.g., by the bit error rate (BER), is at a certain threshold level. This is repeated for all directions relative to the DUT. The sensitivity pattern is then integrated to find the TIS of the DUT. It gives the sensitivity of the DUT in an average sense. Because the measurement is carried out with active mobile terminals, a base station simulator is required to establish a connection with the terminal and to read the signal quality reported by it.

3.1.4 Mean effective gain

The mean effective gain (MEG) is a parameter that describes the performance of the DUT in a realistic mobile environment. It is influenced by the characteristics of the radio channel and the orientation of the DUT with respect to the radio channel environment. It is defined as [13]

$$MEG = \int_0^{2\pi} \int_0^\pi \left\{ \frac{XPR}{1 + XPR} G_\theta(\theta, \varphi) P_\theta(\theta, \varphi) + \frac{1}{1 + XPR} G_\varphi(\theta, \varphi) P_\varphi(\theta, \varphi) \right\} \sin \theta d\theta d\varphi, \quad (3.1)$$

where $G_\theta(\theta, \varphi)$ and $G_\varphi(\theta, \varphi)$ are the θ and φ components of the DUT power gain pattern, $P_\theta(\theta, \varphi)$ and $P_\varphi(\theta, \varphi)$ are the normalized angular power densities of the incoming waves in the radio channel under consideration, and XPR is the mean cross-polarization power ratio of the incoming waves. The MEG is not included in the latest standards for mobile terminal OTA testing [11] [14], but is sometimes used for performance evaluation. In an isotropic environment, the MEG is equal to the TRP (apart from simple scaling) [15].

3.2 Measurement systems

In this section, some common techniques for measuring the aforementioned parameters are described. In general, the scanning surface applied in the measurements may be, for example, planar, cylindrical or spherical. Since this thesis is concerned with the measurement of mobile terminal antennas where all directions relative to the device under test (DUT) are of (nearly) equal importance, the discussion will be restricted to spherical measurements.

3.2.1 System configurations

Single-probe measurement systems are usually implemented either with a stationary probe and rotation of the DUT about 2 axes, or with a probe moving on an arc and rotation of the DUT about one axis. Either way, all directions relative to the DUT are covered by the probe antenna, resulting in a complete spherical scan. These arrangements are depicted in Fig. 2.

The measurement chamber is designed so that interaction between the DUT and the probe through other than the line-of-sight (LOS) path is minimized. This is achieved by covering the walls and surfaces of the chamber with absorbing material that reduces the amplitude of the reflected signals. Then, it can be assumed that the measured voltage is proportional to the amplitude of the LOS signal so that the radiation pattern of the DUT can be determined.

3.2.2 Far-field technique

Usually, one requires the knowledge of the antenna performance in the far field, i.e., far away from the antenna. Beyond a certain distance from the antenna, the relative radiation pattern no longer changes with distance. This is defined as the far-field region of the antenna. Conventionally, for electrically small antennas, the far field is defined to begin at a distance given by the larger of the following criteria [16]:

$$r_1 = \frac{2D^2}{\lambda} \tag{3.2}$$

$$r_2 = \frac{\lambda}{2\pi} \tag{3.3}$$

Here, D is the maximum cross-section dimension of the DUT and λ is the wavelength. r_1 gives the extent of the so-called radiating near-field region, and r_2 the reactive near-field region. Of course, in reality there are no clear-cut borders between different regions but these conditions give the limit, beyond which the near-field effects are typically assumed negligible. The conditions are equal for $D \approx 0.28\lambda$. For antennas larger than this, r_1 must be selected, and vice versa.

The simplest way to determine the far-field performance of the antenna is to set the measurement distance large enough so that the measurement is performed in the far field directly. This is the traditional far-field measurement technique. At microwave frequencies, this condition is typically fulfilled with electrically small antennas (such as mobile terminal antennas) even with fairly short measurement distances. If the condition is not fulfilled, near-field effects may have a significant influence on the measurement values. In this case, the near-field to far-field transformation theory should be applied to obtain reliable results.

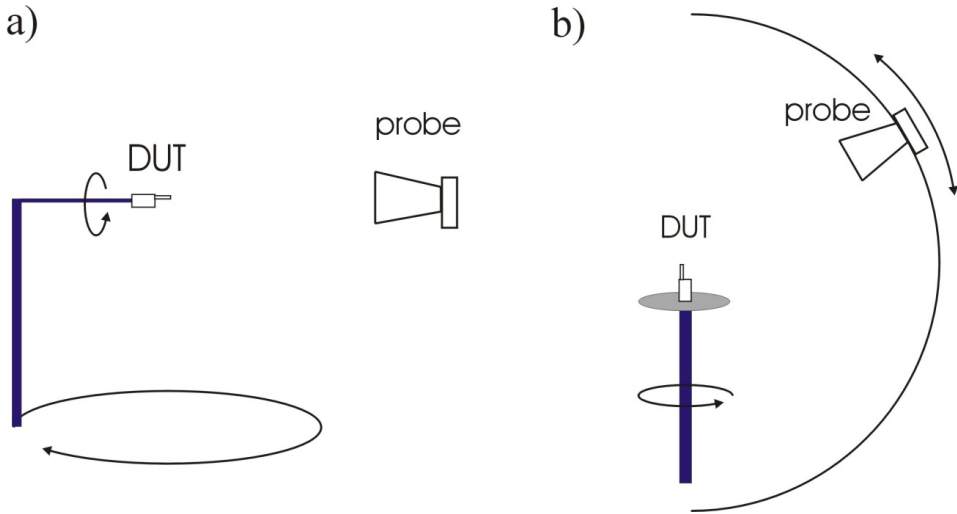


Fig. 2. Configurations of a single-probe measurement system. a) stationary probe and rotation of the DUT about 2 axes b) movable probe and rotation of the DUT about 1 axis.

3.2.3 Spherical near-field technique

In the spherical near-field technique, the measurements are performed in the near region of the DUT, and the far-field performance of the DUT is then determined computationally. Electromagnetic theory provides a solid foundation for this transformation between the near field and far field. The theoretical basis of the spherical near-field technique, shortly discussed in the previous chapter, is well understood and the technique is applied for high-accuracy measurements of, for example, satellite antennas [3].

The main advantage of the spherical near-field technique is that measurements can be always performed near the antenna; large measurement distances are not needed, no matter the size of the DUT. Also, since the measurement is performed over a closed (spherical) surface, no truncation error results from this and the DUT pattern in all relative directions can be determined. As discussed in the previous chapter, the main focus of this thesis is in the applications of the spherical near-field measurement theory.

3.2.4 Other techniques

Other techniques for measuring the antenna radiation characteristics are, for example, the reverberation chamber technique and the compact antenna test range (CATR) [17]-[19]. The reverberation chamber technique has been proposed for the measurement of the radiation efficiency, and for the measurement of multi-antenna terminals to test for the influence of the radio propagation environment on the antenna system performance. It is discussed in more detail in Chapter 6.

In the CATR technique, a plane-wave field is produced in the test zone by using a collimating element such as a reflector or a hologram to convert the spherical wave radiated by the probe into a plane-wave in a compact range. It is mainly used in the measurement of large antennas operating at high frequencies (e.g. satellite antennas), for which the standard far-field criterion produces very large measurement distances. For electrically small antennas, the far-field distance is short and it is, therefore, not necessary to use a CATR-type range.

3.3 Review of reflection compensation methods

In the past decades, there has been a lot of work done in the area of antenna measurement correction techniques. The goal in these techniques is to compensate for the effect of spurious and stray signals in the measurement caused by the non-ideal measurement environment. This thesis includes some contributions in this area so a

short review of such techniques is presented here, with the discussion partly based on the survey given in [20].

3.3.1 Time and frequency techniques

These techniques utilize the additional information gained by performing the antenna measurement as a function of frequency. The frequency and time responses are related through the Fourier transform and are thus equivalent in the sense of additional information they provide.

The time gating technique consists of the transmitter sending a short pulse (with wide frequency content) as the test signal [19] [21] [22]. The multipath components arrive to the receiver (DUT) later than the direct LOS component, and can thus be filtered out either by switching (hard gating) or by signal processing (soft gating). In the soft gating, there is an option to perform the measurement in the continuous-wave (CW) mode at multiple frequencies.

In the matrix-pencil method, the signal received by the DUT is represented as a sum of complex exponentials [23] [24]. Each exponential represents a different propagation path between the transmitting and receiving antennas. The amplitudes of the exponentials can be solved from measurements over frequency, and give the strength of each signal component. It is then possible to set the spurious components to zero and calculate what the measurement result would be in an ideal measurement environment. It is suggested that compared to Fourier-transform-based methods, the matrix-pencil method can better handle narrow-band signals [25].

A similar technique for separating a signal to its components is based on the oversampled Gabor transform. This technique is discussed in [26] and shown to be more robust than the matrix-pencil method.

The equalization technique consists of using an inverse channel filter to correct for the non-flat frequency response of the measurement channel [27]. The impulse response of the measurement channel is first determined by using a pseudo-random bit sequence as a training signal. Once the channel is characterized in this way, it is possible to determine the weights of the filter needed to realize a flat channel response, resulting in cancellation of the effect of signal reflections in the measurement chamber.

Another method based on channel equalization is the time-reversal electromagnetic chamber technique [28]. In this technique, a reverberating measurement environment is utilized so that by properly adjusting the signals radiated from fixed probe antennas, wave fronts impinging on the DUT from any direction can be produced. This technique

requires a calibration measurement to determine the channel response functions prior to the DUT measurement.

The major limitation with the techniques in this category comes from the wideband nature of the measurement signal. Many practical antennas are narrowband structures, whose radiation characteristics may change rapidly over frequency. The use of a wideband measurement signal may thus not be feasible and, consequently, time and frequency techniques are not suitable in such cases.

3.3.2 Spatial techniques

The spatial techniques require measurements of the DUT radiation pattern in several different DUT positions. Due to their different spatial frequencies, the direct and reflected signals add differently in different positions, which enables them to be separated from each other, at least to some extent. The true DUT pattern can then be retrieved in different ways.

In the antenna pattern comparison (APC) technique, the true DUT pattern is approximated as the average of the different measured patterns [29]. This requires many measurement positions for good accuracy. The novel APC method phases the signals received in different known positions so that the direct signals add in phase, and uses a circle-fitting algorithm to determine the correct pattern [30].

In the virtual array method, the DUT is measured twice so that in the second scan its displacement is a function of the rotation angle [31] [32]. It is assumed that one stray signal component is received through the DUT main beam in each rotation angle (this assumption is justified by the fact that a stray signal has maximal effect when received through the main beam). The displacement at each rotation angle is determined so that the direct signals add in phase, and the stray signals add out-of-phase. Effectively, a virtual array is created with a null in the main beam direction and a maximum in the desired direction.

The virtual array concept can also be utilized with the probe antenna, which is the basis of the plane-wave synthesis method (see Chapter 7 in [3]). In [33], a technique is presented, where the probe is scanned on a plane so that it forms a virtual array with pattern maximum in the DUT direction, and minimal radiation elsewhere, so that reflections from the environment are suppressed. This, of course, increases the measurement time considerably.

The adaptive pattern strategy operates in a similar way, but employs a special algorithm to find the directions of arrival (DoA) of the reflected signals (assuming the probe is in the receiving mode) [34]. The weights of the virtual array are then selected to have nulls

in these directions. This method requires less degrees of freedom (i.e., less probe positions) in the virtual array if a limited number of stray signals are present in the chamber.

Recently, techniques have been presented that, although they do not require several measurements of the DUT, can be listed in the category of spatial techniques [35] [36]. These techniques operate in the spherical-wave domain and utilize over-sampled measurements with the DUT offset from the origin of the measurement coordinate system. After the far-field pattern calculation, the DUT is computationally translated to the coordinate system origin. Then, the measurement data is filtered in the spherical-wave domain, resulting in suppression of the fields from secondary sources. These techniques are not exact in that they do not, even in theory, eliminate the effect of extraneous signals, but only reduce it.

3.3.3 Techniques based on test zone field measurement

The techniques in this category are based on measurement of the test zone field with a known reference antenna. The test zone field includes the effects of the direct signal and the reflected signals. This knowledge can be used in the DUT measurement to determine its radiation pattern accurately.

The signal received by an antenna in the test zone is a convolution of the antenna radiation pattern and the plane-wave spectrum of the test zone field. If one of the latter two is known along with the measured signal, the other can be solved by deconvolution [37] [38]. It is also possible to use a matrix-inverse calculation technique to obtain the solution [39].

The test zone field (TZF) compensation method employs a spherical-wave field model [40]. It is computationally more demanding than the aforementioned simpler techniques but has some advantages over them. In the spherical-wave domain, empirical rules for properly truncating the field expressions based on the test zone and DUT size can be utilized. Also, near-field effects can be included in the analysis. The computational complexity of the TZF method is $O(N^3)$. A downside of this technique is that it is iterative, which may entail some convergence problems, especially in environments with reflections of high amplitude.

A modification of the test zone field compensation method is the plane wave pattern subtraction method, which is also iterative, but has lower computational complexity [41]. It can be applied in far-field and compact antenna ranges.

All the methods in this category require additional measurements with an external calibration antenna. However, the calibration measurement typically needs to be

performed only once, after which the same calibration data can be applied for all measurements where the DUT minimum sphere is not larger than the calibration antenna minimum sphere, assuming the measurement range characteristics have not changed. Furthermore, the information obtained on the test zone fields may be useful also for other purposes, such as finding the dominant sources of error in a given measurement range.

3.4 Contributions of this thesis

In this thesis, a reflection compensation method has been developed that can be applied in environments exhibiting high reflectivity levels [I] [II]. The new method is a modification of the TZF compensation method [40] and is based on the spherical-wave theory. Therefore, it utilizes an accurate field model with well-known truncation rules based on the size of the test zone and is in this sense better than the simpler models in the TZF measurement category [37]-[39]. Since the time/frequency techniques and the spatial techniques have their own limitations (measurement over frequency, multiple DUT measurements) the developed new method will be here contrasted with similar techniques in the TZF measurement category.

The computational complexity of the modified TZF compensation technique, $O(N^6)$, which results from the matrix inversion, is higher than in the original TZF compensation, $O(N^3)$ [I] [II] [40]. Therefore, the modified TZF compensation is best suited for measurement of electrically small antennas. However, in the modified TZF compensation the matrix inversion is required only in the calibration part, which does not need to be repeated as long as the measurement environment remains unchanged. In the DUT measurement, all that is required is a matrix multiplication [I]. The computation times for the measurements presented in [I] (truncation number $N = 8$) were in the order of few seconds with a standard PC.

The modified TZF compensation is superior to the original method (and its plane-wave modification [41]) in that it is not iterative and there is no constraint on the amplitude of the reflected signals. Therefore, the new method enables antenna measurements in, for example, normal laboratory rooms as demonstrated in [I]. In theory, the reflections can be of arbitrarily high level, because the direct probe signal has no special status in the method. The fields entering the test zone, whatever they are, are measured and this information is then used in the DUT measurement. Naturally, practical considerations such as the dynamic range of the measurement equipment need to be taken into account, as in any measurement scenario. Also, multiple reflections between the DUT and the surroundings must be assumed negligible because the method does not account for them. A well-known technique for reducing the error from multiple reflections in traditional antenna measurements is to perform the measurement with different DUT locations and average the results. However, the author is not aware of multiple

reflection error reduction techniques applicable for test zone field compensation, except the use of low-scattering probes.

Since the modified TZF compensation is based on the spherical-wave theory, it is capable of including and compensating radiating near-field effects, and can therefore be applied in near-field measurement ranges. The type of the measurement range probes is not restricted in the method, but any types of practical probes can be used. Of course, it is desirable that the probes are well-suited for antenna measurements, i.e., radiate strongly towards the test zone and little elsewhere, are well-matched, etc. However, the defects of these practical probes, such as the polarization errors and the signal reflections caused by back-lobe/side-lobe radiation and scattering (excluding multiple scattering between the DUT and the probe), are corrected by the modified TZF method. A further benefit is that the new method also enables the use of irregular measurement grids during both the calibration measurement and the DUT measurement.

Independently, at the same time, another, quite similar method has been developed by Pogorzelski for compensating the room effects in antenna measurements [42] [43]. The modified TZF method developed in this thesis was first presented in the spring 2009 [II] and Pogorzelski's method in the fall 2009 [42]. In Pogorzelski's method, termed the extended probe instrument calibration (EPIC) method, the combination of the measurement environment and the probe is viewed as an "extended" probe, whose response to each spherical mode radiated from the test zone is determined through measurements with a calibration antenna. This information is then used in the DUT measurement to correct for the effect of the environment.

The EPIC method places no restriction on the amplitudes of the signal reflections, either. It is not, however, entirely similar to the modified TZF compensation method. The EPIC method requires a double-scanning over the measurement sphere. The computational complexity of the EPIC method is lower, $O(N^4)$, than that of the modified TZF compensation, which is an advantage [42]. This has, however, the consequence that irregular measurement grids cannot be used with it. Also, in the modified TZF compensation method, the TZF calibration measurement can be performed, e.g., with a calibrated probe array. The radiation characteristics of the probe array elements need not be similar. Another difference is that the modified TZF method produces an explicit spherical-wave model for the test zone fields. This information can be used, for example, in range evaluation. Finally, unlike the EPIC method, the modified TZF method has been demonstrated both with single-probe and multi-probe systems [I] [II].

4 Measurement of antenna radiation characteristics: multi-probe systems

In the past couple of decades, multi-probe antenna measurement systems have emerged as an alternative to traditional single-probe systems. They are nowadays widely used in the testing of electrically small antennas. Multi-probe systems have their own characteristic advantages and disadvantages, which are discussed in this chapter.

In the first two sections, typical probe and system configurations are presented. In the following two sections, the advantages and challenges of multi-probe systems, compared to single-probe systems, are discussed. The contributions of this thesis to multi-probe antenna testing are summed up in the last section.

4.1 Probe configurations

A number of different probe configurations are used in multi-probe measurement systems. These configurations vary with respect to the number and locations of the measurement probes. Some of the most common configurations for small-antenna measurements are the arc, the circle, and the spherical configurations. These are discussed in the following.

4.1.1 Circle and arc configurations

In the circle and arc configurations, the probes are installed on a (vertical) plane so that they form either a half-circle or a circle [44] [45]. These configurations are depicted in Fig. 3. The DUT is placed in the middle of the circle and rotated around the azimuth angle so that its radiation to all directions can be measured. The half-circle configuration requires full 360° azimuth rotation, whereas the circle configuration requires 180° rotation. Geometrically, these configurations are similar to the single-probe system setup shown in Fig. 2b, with the difference that the movable probe is replaced by a probe array, and thus mechanical scanning is replaced by electrical scanning.

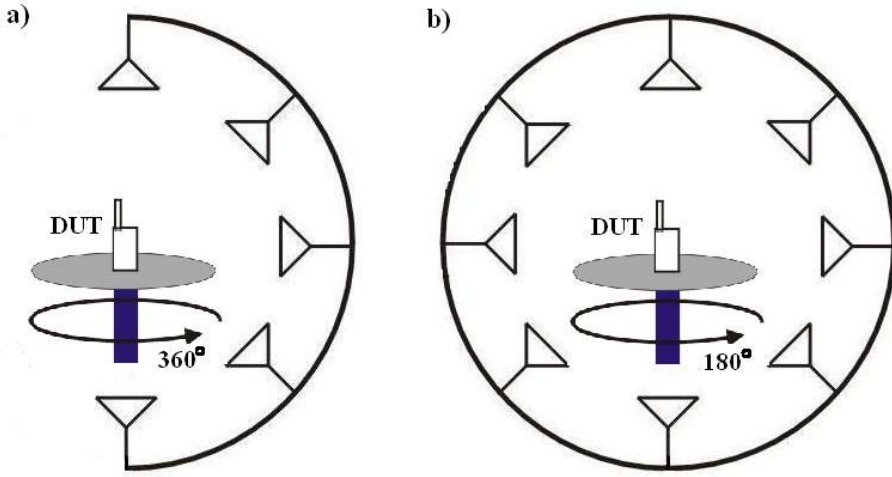


Fig. 3. Probe configurations of multi-probe antenna measurement systems. a) half-circle b) full circle.

4.1.2 Spherical configuration

In the spherical configuration, the probes are distributed on a spherical surface [46] [47]. Measurement samples can be thus obtained uniformly all around the DUT without rotating it. Fig. 4 shows the measurement system presented in [46], which employs a spherical probe configuration, and improvements upon which are developed as part of this thesis.

The spherical probe configuration understandably requires a large number of probes, which makes the system more complex. Minimization of the number of probes, while still retaining desired measurement accuracy is, therefore, an important question with these systems. It has been shown that the use of complex field samples as opposed to amplitude-only samples results in more accurate field characterization with a given number of measurement points [48]–[50]. As part of this thesis, the multi-probe system of Fig. 4 has been equipped with phase-retrieval capability, which allows the measurement of complex field values with active mobile terminals, where a feed cable measurement with a vector network analyzer (VNA) is not possible [III].

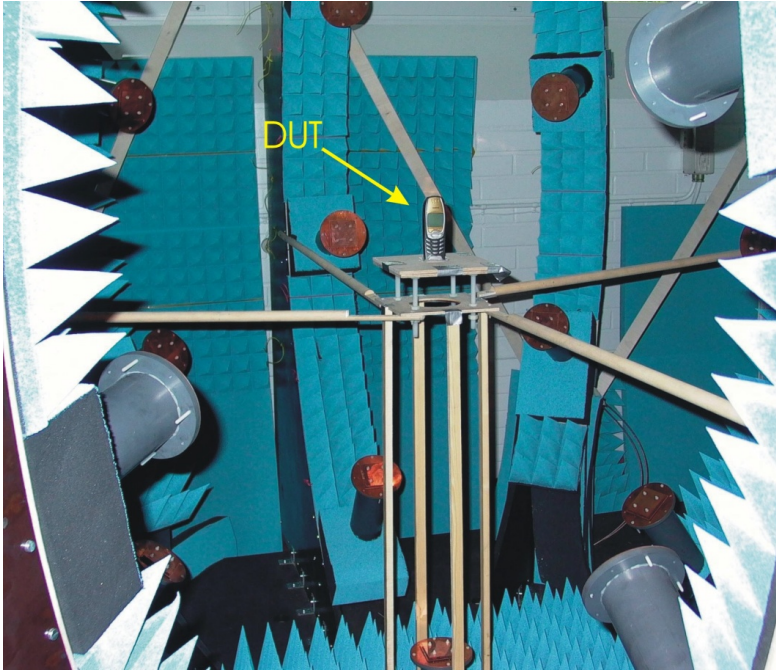


Fig. 4. A multi-probe system utilizing a spherical probe configuration.

4.2 System configurations

Multi-probe systems require a signal distribution network, which connects the measurement signals corresponding to each probe sequentially to the measurement instrument. A microwave switching network is typically required for this, as depicted in Fig. 5. When measuring active mobile terminals, a base station simulator is required to set up the connection to the DUT and control its transmission. In this case, there is no feed cable going to the DUT, and the measurement instrument is typically either a spectrum analyzer or a power meter.

An alternative method is the modulated scattering technique, where the DUT transmits the measurement signal, which is then modulated and scattered by the probes [51]. The modulation is performed with each probe one at a time. The scattered signal is then recorded by using either an auxiliary probe or the DUT as the receiver. This technique requires only a low-frequency switching network because a low-frequency modulation signal is used with the probes.

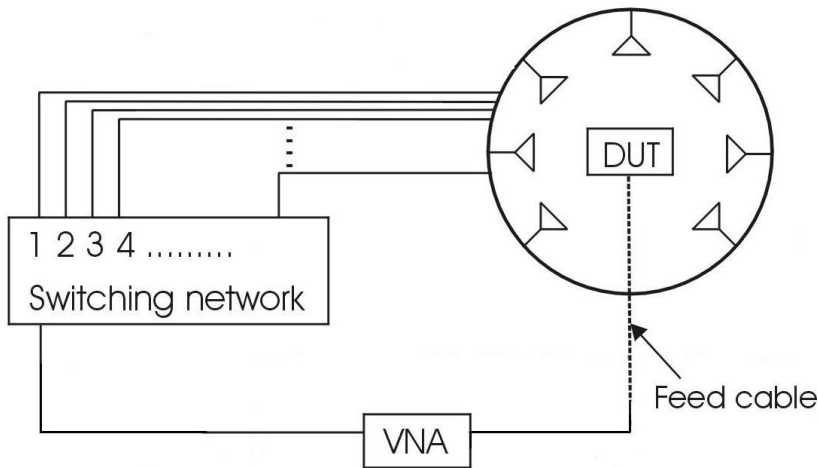


Fig. 5. In a multi-probe measurement system, a switching network connects the measurement signals from each probe to the measurement instrument.

4.3 Advantages over single-probe systems

Multi-probe systems provide some advantages over single-probe systems in antenna testing. The most significant of these is the drastic reduction of test times, which can be very important, e.g., in the product development of mobile terminal antennas. Where typical test times for radiation pattern measurement with single-probe systems are in the range of hours or tens of minutes, with multi-probe systems they are in the range of minutes, or even seconds.

Another advantage is the reduced requirement for the functionality of the DUT positioner. Typically, scanning of the DUT is required only around one axis at the most (circle and arc probe configurations). With the spherical configuration, rotation may not be required at all. This means that a positioner with an azimuth scanning capability is sufficient in multi-probe systems. Also, the installation of the DUT is thus easier because it does not need to be fixed to withstand rotations in multiple directions. This is crucial if measurements are performed with test persons, because in such situations only azimuth rotation is feasible. Of course, azimuth-only rotation may be implemented also with single-probe systems by the use of a movable probe as discussed in Section 3.2.1, but the measurement time limitations will still remain with such a setup. Measurements with test persons are discussed in the next chapter.

4.4 Challenges

Multi-probe systems face their own distinct challenges, which mainly stem from the more complex system structure. The use of a large number of probes requires an extensive signal distribution network with a large amount of cabling, switches etc. These components are lossy and may limit the dynamic range of the measurement system. Also, the cost of such a system may become very high, depending on the quality requirements for the components. The system control software is more complicated, because it must control the switching network as well as the measurement instruments, with synchronized timing. On the other hand, the positioner control may be simpler.

One of the biggest challenges with multi-probe systems is the system calibration. Since the system utilizes multiple measurement channels, the differences in the channel responses must be calibrated out for the measurement result to be reliable. A simple way to do this is to measure the S_{21} parameters of the measurement channels using a VNA. This kind of calibration measurement accounts for the differences in the cables and switches (assuming the response of the switches is repeatable enough). However, there are also differences in the probe responses of the system and it is desirable to calibrate those, as well. For this, a directive reference antenna may be used, which is fed with the VNA and pointed towards each probe in turn, while measuring the response of the signal path [52].

An additional problem with multi-probe systems is that, as a result of placing multiple measurement probes in the measurement chamber, the anechoic properties of the chamber deteriorate. The mutual coupling between the probes corrupts the test zone field, resulting in increased measurement uncertainty. This effect can be alleviated to some extent by the use of directive probe antennas [53]. It would be, however, desirable to find a calibration method to cancel the effect of signal reflections in the measurement chamber. The test zone field compensation method, discussed in the previous chapter, is such a method and it is shown in [II] how it can be adapted to calibration of a multi-probe measurement system. This new calibration method accounts for the differences in the channel responses of a multi-probe system, including the effect of the probes and the signal reflections and leakages in the measurement chamber.

4.5 Contributions of this thesis

The contributions of this thesis with respect to multi-probe system development are contained in publications [II]–[IV]. In [III], the spherical multi-probe system presented in [46] is equipped with a phase-retrieval network. This network is able to retrieve the phase of the field radiated by the DUT from amplitude-only measurements. Such functionality is useful because the availability of the phase information increases the accuracy of the field characterization. The phase of the field cannot be measured

directly with active DUTs utilizing their own transmitters because in such measurements a feed cable cannot be used and a VNA measurement is, therefore, not possible. For validation of the phase-retrieval technique, test measurements are carried out with a mobile terminal prototype antenna, using a feed cable. The phase values measured directly with a VNA are compared to those calculated from amplitude-only measurements performed with a spectrum analyzer, using the phase retrieval network. It is shown that the results are in good agreement.

In [IV], the functionality of the multi-probe system is improved and investigated as a function of frequency. The measurement speed of the system is enhanced such that full radiation pattern measurements can be performed in seconds rather than minutes (also, the computation times required for the field characterization are very short, in the order of seconds with a standard PC, due to the small number of measurement points). Furthermore, the operating frequency range of the system is extended significantly. Test measurements are performed over a large frequency range with a typically-sized multi-band mobile terminal antenna model as the DUT. By comparison with simulations and measurements performed in a standard, single-probe anechoic chamber, it is investigated how the small number of measurement points affects the measurement accuracy, as the electrical size of the DUT increases. It was found that the number of measurement points in the system (64) was sufficient for characterization of the DUT field pattern up to 2 GHz but above this frequency the accuracy degrades noticeably. Also, the accuracy of the phase-retrieval network was studied against reference measurements over a wide frequency range and the repeatability of the system was investigated by measuring the DUT in different orientations.

In [II], a novel calibration method for multi-probe antenna measurement systems is presented. The method incorporates measurement of the test zone field corresponding to each probe with a known reference antenna. A spherical-wave model is created for the test zone fields and then utilized in the DUT measurement to cancel the effect of the non-ideal test zone field. The method accounts for the channel balance calibration, and for the signal reflections between the probes and surfaces of the measurement chamber. Test measurements are carried out, where the new calibration method is compared to standard S -parameter calibration and also to external reference measurements in a high-accuracy spherical near-field range. In the test measurements, similar measurement accuracy (compared to the external reference) was achieved with the new calibration method and with the S -parameter calibration. It is noted that the performance of the TZF calibration method can be enhanced by improving the measurement accuracy of the TZF measurement (with the known reference antenna).

5 Effect of the human body on mobile terminal antenna performance

Mobile terminals are typically held close to the body during usage, which means the antenna does not operate in free-space conditions. The electromagnetic properties of the human body may significantly alter the performance of the mobile terminal. Therefore, it is important to be able to test for this effect during the product development of mobile terminal antennas.

This chapter deals with the testing of user influence on the mobile terminal antenna performance. Section 5.1 describes the mechanisms, through which the human body affects the radiation characteristics of mobile terminal antennas. In Section 5.2, the typical measurement methods used in testing this effect are discussed. Section 5.3 gives an overview of the research results found in the literature on the influence of the human body on the mobile terminal performance, focusing on measurements with live test persons. Contributions of this thesis in this area are listed in Section 5.4.

5.1 Influence mechanisms

The human body is a large object of lossy, dielectric material, which, when located in the near field of a radiating antenna, influences the antenna's radiation characteristics significantly. Changes of the complex field amplitude are effected in the radiation pattern. Radiation to some directions is reduced because of the shadowing caused by the body, and the overall transmitted power is reduced because part of the power is absorbed in the tissues of the body. For the link performance of the communications system, this is detrimental because the link quality obviously depends strongly on the amount of transmitted power between the two ends of the link.

All the power that is dissipated in the body tissues is wasted from the communication point of view and should be, therefore, minimized. A further drawback is that, when a large portion of the transmitted power is lost in the tissues, the mobile terminal needs to operate at higher output power levels to maintain the required link quality. This results in faster consumption of the mobile terminal battery and reduces its operation time.

The body also causes a change of input impedance in the antenna port of the mobile terminal, which affects the power accepted by the terminal antenna [54]. This effect is often detrimental but may in some cases be beneficial depending on whether the antenna matching in the operating frequency is improved or degraded.

The difference in the total radiated or received power between the free-space measurement and the measurement in the proximity of the body is termed the body loss (BL). The BL represents the total effect of the human body on the efficiency of the antenna and both effects discussed above (absorption and impedance change) contribute to it. The BL typically depends strongly on where the mobile terminal is located with respect to the body and how it is held by the user. Therefore, in order to determine the average BL, a large number of measurements is required, as discussed in the next sections.

5.2 Measurement methods

Measurements of the user effect can be performed in two ways. Either an artificial representation of the human body is used in the measurements, or live test persons are used. These two cases, respectively, are discussed in the following sections.

5.2.1 Measurements with phantom

Measurements of BL can be carried out by simulating the user with a so-called phantom, which has a similar form as the human body. The phantom is filled with a tissue-simulating liquid with dielectric properties resembling those of human tissue. Fig. 6a shows an example of a phantom that can be used to imitate the head of the user during the measurement. The DUT is attached on the side of the phantom in a position corresponding to normal usage by the ear (excluding the hand).

Measurements with the phantom have the advantage that the position of the DUT with respect to the phantom can be defined accurately and the measurements are possibly more repeatable than measurements with real test persons. Also, the test object can be rotated in many directions and the measurement time limitations are not as severe as with live test persons. A drawback is that the results are only representative and no information on the statistical variations encountered in actual usage scenarios is obtained.

It has been shown that measurements with a head phantom give a good indication of the effect of the human head on the mobile terminal antenna performance in an average sense [V] [55]. Measurements with head phantoms have also been included in the test standards [11] [14]. However, it is also understood that the hand has a significant impact on the operation of the mobile terminal, and is often the larger contributor to the BL [56] [57] [V]. Moreover, the hand can be critical in other usage modes, such as the browsing mode, in which the mobile terminal is held in front of the user in a way typical for mobile web browsing.

It is much more difficult to design standardized hand phantoms that could be used in the measurements in a similar way as the head phantoms. The hand phantom needs to be flexible to allow grips with phones of several types. Also, it is difficult to define a standard grip that is applicable with different phones. Furthermore, it can be questioned how meaningful such a “standard grip” would be, since in actual use, the mobile terminal is anyway held in many different ways [58]. These complications are the reason why hand phantoms have been less often used. Nevertheless, progress is being made in the standardization of hand phantoms and grips to include them in the test standards [59].

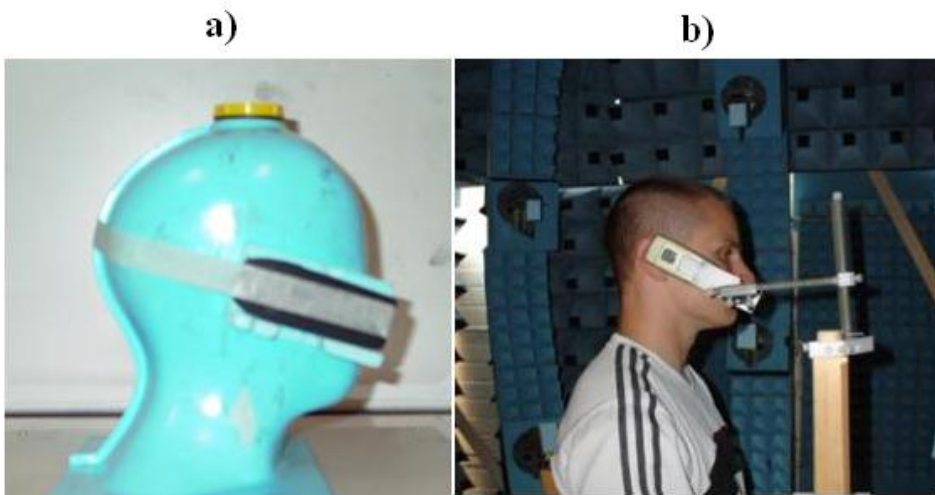


Fig. 6. a) head phantom that can be used to simulate the effect of the user in the measurement b) measurement setup with live test person.

5.2.2 Test person measurements

Test person measurements are the way to test the operation of a mobile terminal antenna in conditions resembling the actual usage situation as closely as possible. In these measurements, the performance parameters are sampled while the persons hold the DUT in a normal usage position. As with phantom measurements, the DUT can be either an antenna prototype, possibly installed on a phone chassis, or an actual operating mobile terminal. As the proximal area the DUT sees is similar to that in real usage situations, the measured parameters are realistic and represent the performance in an actual usage scenario.

Due to the variety of ways the mobile handset can be held with respect to the body, it is difficult and time-consuming to study by measurements the effect of the user on its

performance. A large number of test persons and measurements are typically required in order to gain information on the performance of the DUT in an average sense. Due to the individual grips and anatomy of the test persons, large variance of the measured parameters is usually observed, meaning that individual test results may be far from the average. This is why reported measurement campaigns with test persons often have a large number of test persons and the results are interpreted statistically [56]-[65].

Test person measurements have, however, their own difficulties. The minimization of the measurement time becomes particularly important for two reasons. First, it should be possible for the test persons to remain motionless for the duration of the measurement. Second, since a large number of measurements are typically required, a fast measurement is desirable. This is why single-probe measurement systems are often out of the question in test person measurements, and multi-probe systems are preferred. Furthermore, with test person measurements, for obvious reasons, rotation of the DUT is feasible only about the azimuth axis. As discussed in Chapter 4, multi-probe systems usually fulfil this requirement. Fig. 6b shows a test person measurement setup with a spherical multi-probe system, where no rotation at all is required. Test person measurements have been performed also with single-probe systems, but this necessitates the use of a movable probe [55] [60].

5.3 Survey of reported test person measurements

A number of measurement campaigns aimed at studying the effect of the human body on mobile terminal antenna performance with live test persons have been reported in the literature. This section presents a survey of the results of these tests, focusing on those where the measurements have been performed with several test persons.

In [56] and [57], the performance of mobile terminal antennas in the GSM900 and GSM1800 bands, respectively, was studied with 15 test persons using a multi-probe measurement system. The study included different types of antennas and the evaluated parameters were the efficiency, the BL and the MEG. The measured average BLs were 10.9 dB (GSM900) and 7.7 dB (GSM1800). Also, for most antenna types, the hand was a larger contributor to the total BL than the head. The corresponding average MEGs were reported at -14.6 dB and -14.8 dB.

In [60], the contribution to the total BL from antenna impedance mismatch and power absorption was studied through measurements in an anechoic chamber. The number of test persons was 36. It was found that the major part of the BL is caused by the power absorption in the body. This is confirmed also by the measurement results in [56] and [57].

Test person measurements have been also performed in urban radio channel environments by using a radio channel sounder. In [61] and [62], the average power received in an urban radio channel environment (in the GSM1800 band) by different mobile terminal antennas was studied with a group of 200 test persons. The variations in the average received power within the group were found to be considerable, up to 10 dB. The average BL was between 3 and 10 dB, depending on the antenna type. Furthermore, it was shown that it is sufficient to have 13 test persons to estimate the mean body loss with a 90% confidence interval of ± 1 dB regardless of the antenna type.

Measurements in real radio channel conditions at 900 MHz are reported in [63] and [64] for groups of 20 and 30 persons, respectively. The measured mean BL values were 8.4 and 8.9 dB, with standard deviation of approximately 3 dB. However, in these measurements the antenna in the reference measurement for the BL values was not the same as with the test persons, but a half-wave dipole, so the obtained values do not correspond to the standard BL definition.

Measurements have also been performed in live cellular networks by utilizing the in-built power-reporting feature of these networks. Such measurements with 12 test users are reported in [65]. The used test parameter is the link loss, which is obtained by comparing the transmitted and received power levels during a call reported by the network. The differences in the link loss between users were mostly between 3 to 6 dB, but in some cases up to 14 dB. The mean BL was in the range of 2 to 11 dB, depending on the antenna type. Mobile terminals with external antennas resulted in lower mean BLs in this study.

In [55], the BL was studied through measurements in an anechoic chamber in the GSM1800 band with three test persons. In these measurements, each test person used a similar, pre-defined grip on the phone. Very small variation (0.2 dB) was found between the BL values of different test persons. The average body loss due to the head was reported at 1.6 dB and the additional loss due to the hand at 2.6 dB.

There have also been some investigations on the effect of the body with other usage positions such as the body-worn, or the “browsing” position [66] [67]. In [66], significant performance differences were not found between the typical next-to-head usage position and the browsing position. However, the body-worn set-up (waist) was found to be the worst in terms of efficiency and MEG. In the in-network measurements reported in [67], the mean BLs in different body-worn positions varied between 3.5 and 9.5 dB, which is comparable to similar measurements with the normal next-to-head usage position [65].

5.4 Contributions of this thesis

The contributions of this thesis in the area of test person measurements are contained in [V], where the results of two measurement campaigns are reported. The first measurement campaign is carried out with a single-probe measurement system with three test persons, whereas a multi-probe system is used in the second measurement campaign, the number of test persons being 13. The multi-probe system is the one discussed in the previous chapter and in [IV], and is well-suited for test person measurements due to the fast measurement and the lack of need for rotating the DUT during the measurement.

One concern with this multi-probe system, however, is the small number of measurement samples (32 dual-polarized samples). In test person measurements, the combination of the mobile terminal and the test person forms the DUT, which is therefore very large, indicating that in these measurements condition (2.4) is not met. There may thus be large errors in the measured radiation pattern of the DUT. However, the relevant parameter in these test person measurements is the TRP, which is an integrated quantity and, therefore, less susceptible to the error resulting from the small number of measurement samples. Furthermore, the results show good agreement with the single-probe system measurement results, where the number of measurement points was much higher, lending further confidence to the assumption that the applied number of samples in the multi-probe measurements was sufficiently high for the determination of the TRP [V].

Previous studies have shown that the BL between different people varies considerably. However, systematic studies have not been performed as to the reason of this large variance. In [68], a correlation was found in test person measurements between the BL and the hand position over the mobile terminal, but other factors in the tests were not controlled. The main focus in [V] was to determine conclusively the reason for the large differences in BL between people. It was shown that when the position of the phone and the grip used by the test persons is pre-defined and similar for all users, the variance of the BL results decreases greatly. Measurements were performed both in the GSM900 and in the GSM1800 band with a dual-band monoblock phone with an internal antenna. No feed cable was used, but the connection to the phone was established with a radio communication tester and the radiated complex field pattern determined from amplitude measurements as discussed in [III].

The standard deviation of the TRP between the 13 test persons was 3 dB and the maximum difference was 8 dB, when the users were holding the phone in a freely-selected way. The standard deviation dropped to 0.8 dB (0.4 dB) at 900 MHz (1800 MHz), when all the users applied the pre-defined grip [V]. Therefore, this shows that the main cause for the large variation between users is the grip style and not other factors such as, e.g., anatomical differences between people. This finding is also

supported by [69], in which it is shown by simulations that small differences in the dielectric properties of the tissues do not cause significant changes in the user effects.

The measured mean BLs were 9.2 dB (GSM900) and 6.2 dB (GSM1800). The separate losses caused by the head and the hand were also studied. The isolated hand losses were found to be 4.1 dB (GSM900) and 3.2 dB (GSM1800) and the corresponding head losses 5.4 dB and 2.0 dB. For comparison, measurements were performed with a head phantom and the measured losses were very close to the isolated head losses measured with test persons (5.8 dB and 1.5 dB). This result indicates that the head phantom is a good representation of the average human head for TRP measurements. Finally, it was noted that, where comparisons could be made, the results with the two different measurement systems were in good agreement.

The results of [V] are well in line with and confirm the results of earlier studies for the applicable parts [56] [57] [61] [62]. The measured average BLs and efficiencies were comparable between these studies. Most importantly, [V] produced new information on the causes for the large differences that occur in the performance parameters between different people. These results were obtained with monoblock-type phones. In future work, it might be interesting to repeat the measurements with different types of phones to study whether, e.g., some phone types are more sensitive to the individual grips than others.

6 Over-the-air testing of multi-antenna terminals

The radio-wave propagation environment has a large influence on the link performance of a mobile communications system. Multiple distinct signal propagation paths result in fading when different signal components combine in opposite phases. It is also possible to take advantage of the distinct propagation paths by using advanced multi-antenna systems. Multiple antenna elements may be utilized in the transmitting side (transmit diversity), receiving side (receive diversity), or both sides (Multiple-Input Multiple-Output, i.e., MIMO systems), which are already being used and deployed in several communications systems. It has been long ago proposed that mobile terminal antennas be tested in actual radio channel conditions [70]. With the new multi-antenna systems, this question has become increasingly relevant.

This chapter discusses the ways to measure the effect of the radio propagation channel on the performance of the mobile terminal antenna system. Here, the antenna system can be understood in a wide sense, including the transceiver architecture and the signal processing algorithms that also play a central part in the overall radio performance of the mobile terminal. The term OTA testing has become widely used to mean the testing of mobile terminal radio performance. In this chapter, the term MIMO-OTA testing is used to refer to the testing of any multi-antenna system.

Section 6.1 discusses the proposed performance parameters for MIMO-OTA tests. In Section 6.2, a brief overview of typical propagation channel models is given. Section 6.3 presents the proposed test methods for the MIMO-OTA testing and Section 6.4 summarizes the contributions of this thesis in this area.

6.1 Figures of merit

In the OTA testing of MIMO and diversity antenna systems, the figures of merit used for single-antenna systems (Chapter 3.1) are insufficient [71] [72]. This is because parameters such as TRP or TIS do not capture the effect of the radio channel on the performance of multi-antenna systems. In these systems, the characteristics of the antenna (such as the radiation pattern) are not static, but may be actively tuned in response to the changing radio channel environment. Therefore, the spatial and temporal properties of the radio channel are crucial in the performance evaluation of MIMO systems.

Because MIMO systems are supposed to exploit the multiple propagation paths of the radio channel to increase data transmission speed, such a performance metric is required that describes how well they perform in this respect. Currently, this question is being considered in the ongoing standardization work of MIMO-OTA test methods in the

COST2100 and the 3GPP forums [73] [74]. No agreement on the performance parameters has been reached yet, but a preliminary set of parameters has been established [75]. Some of the relevant parameters are described in the following.

6.1.1 Diversity gain

The diversity gain is defined as improvement in the time-averaged signal-to-noise ratio (SNR) resulting from the use of multiple antenna elements over single-antenna systems. It is, therefore, also dependent on the algorithm applied in combining the signals from the multiple elements. The reference single-antenna case can be an ideal antenna with 100% efficiency (effective diversity gain), one of the individual antenna elements of the multi-element DUT (apparent diversity gain), or another realistic single antenna (actual diversity gain) [76] [77]. The improvement in SNR is read from the cumulative power distribution curve at a certain probability level, e.g., at 0.01.

6.1.2 Correlation coefficient

The envelope correlation coefficient can be calculated based on the antenna radiation patterns and the propagation model power distribution. It gives a measure of the correlation between the signals in different antenna branches. It is given as [78]

$$\rho_e \approx |\rho_c|^2 = \frac{\left(\int_0^{2\pi} \int_0^{2\pi} X \sin \theta d\theta d\varphi \right)^2}{\int_0^{2\pi} \int_0^{2\pi} Y \sin \theta d\theta d\varphi \int_0^{2\pi} \int_0^{2\pi} Z \sin \theta d\theta d\varphi} \quad (6.1)$$

with

$$\begin{aligned} X &= XPR \cdot E_{\theta 1}(\theta, \varphi) E_{\theta 2}^*(\theta, \varphi) P_{\theta}(\theta, \varphi) + E_{\varphi 1}(\theta, \varphi) E_{\varphi 2}^*(\theta, \varphi) P_{\varphi}(\theta, \varphi) \\ Y &= XPR \cdot E_{\theta 1}(\theta, \varphi) E_{\theta 1}^*(\theta, \varphi) P_{\theta}(\theta, \varphi) + E_{\varphi 1}(\theta, \varphi) E_{\varphi 1}^*(\theta, \varphi) P_{\varphi}(\theta, \varphi) , \\ Z &= XPR \cdot E_{\theta 2}(\theta, \varphi) E_{\theta 2}^*(\theta, \varphi) P_{\theta}(\theta, \varphi) + E_{\varphi 2}(\theta, \varphi) E_{\varphi 2}^*(\theta, \varphi) P_{\varphi}(\theta, \varphi) \end{aligned} \quad (6.2)$$

where XPR is the cross-polarization power ratio, $E_{\psi i}(\theta, \varphi)$ is the ψ -polarized electric field pattern of antenna element i , and $P_{\psi}(\theta, \varphi)$ is the angular power distribution of the ψ -polarized incoming waves. There exists a theoretical connection between the diversity gain and the correlation coefficient [78].

6.1.3 Capacity and throughput

The channel capacity is the theoretical maximum capacity achievable in a communications channel. Assuming no knowledge of the channel at the transmitter, the capacity C can be calculated as [79]

$$C = \log_2 \left(\det \left(\mathbf{I}_{N_r} + \frac{SNR}{N_t} \mathbf{H} \mathbf{H}^H \right) \right), \quad (6.3)$$

where \mathbf{I}_{N_r} is the identity matrix, \mathbf{H} is the channel matrix, and N_t and N_r are the number of transmit and receive antennas, respectively. The channel matrix contains the channel response from each transmit antenna to every receive antenna.

Throughput is a related parameter, which includes the effects of modulation, error correction etc. It is, therefore, a more realistic figure of merit for the performance of actual MIMO systems. Some other channel parameters, which are related to throughput values, have been also proposed, such as the Received Signal Strength Indicator (RSSI) or the Carrier-to-Interference-and-Noise Ratio (CINR) [80].

6.2 Channel models

For the measurement of the performance of MIMO antenna systems, two options seem to be viable. Either the measurements need to be carried out through field tests by taking the DUT and the measurement equipment to the actual operating conditions, or, alternatively, the desired radio channel environments need to be (re)created in the laboratory. The latter option seems preferable, because it is likely to be cheaper, faster and, furthermore, enables repeatable testing schemes and, therefore, a fair comparison of different designs.

In order to create a radio channel for the performance tests of mobile terminals, one needs to first have a model for the channel. Numerous radio channel models representative of certain propagation scenarios have been developed for MIMO systems in the past ten years (see e.g. survey in [81]). These models are often based on large amounts of measurement data obtained with special measurement instrumentation, i.e., channel sounders [82]-[85]. Typically, the models contain information on the complex amplitudes, directions of arrival (DoA), directions of departure (DoD), delays, and possibly also polarizations of the multi-path components.

For meaningful comparison of the performance of different MIMO systems, one requires a reference channel model with well-defined characteristics. Several such reference models have been proposed by different organizations. Examples include the 3GPP SCM, IST-WINNER, IEEE 802.11n, and the IMT-Advanced models [86]-[89]. Comparisons of some channel models from the MIMO-OTA testing point of view have been made [90] [91].

Whatever the selected reference model, the challenge in the testing is to recreate a channel with the properties of the chosen model accurately and in a repeatable manner so that different DUTs can be compared under similar circumstances.

6.3 Proposed test methods

Based on the available radio channel models and the measured radiation characteristics of the DUT, it is possible to computationally determine some DUT performance parameters, when exposed to the channel conditions in question [13] [92]. However, these calculation-based methods do not give information on the real-time interaction between an active mobile terminal and the radio channel. Such information is important in determining the average performance of the DUT, and can be obtained only with measurements. The most common test methods proposed for this purpose are discussed in the following.

6.3.1 Reverberation chamber

In order to reproduce radio channel environments in laboratory conditions, different approaches may be taken. One approach is to aim to reproduce only the statistical properties of typical radio channels. This is the basis of the reverberation chamber method [17]. In this method, the DUT is placed in a closed metal chamber, inside which cavity modes are excited by the use of one or a few probes. These cavity modes are perturbed by the use of moving mechanical stirrers inside the chamber (referred to as mode stirring).

As a result of the mode stirring, a Rayleigh fading environment is created inside the chamber, in which the real and imaginary parts of the voltage induced in the ports of the DUT will have a Gaussian distribution. Furthermore, if a large enough number of modes are excited in the chamber, the angles of arrival of the plane waves entering the test zone are uniformly distributed over the unit sphere [93]. Other means of mode stirring can be also employed, such as platform stirring [94] or frequency stirring [95]. The delay spread of the Rayleigh fading channel can be controlled by loading the chamber with lossy objects. The loading can also be used to create and control a Rician

fading distribution in the chamber since the loads will affect the statistical part of the coupling between the probe antenna(s) and the DUT, but not the direct coupling [96].

The reverberation chamber has been proposed for measurement of the traditional performance parameters in mobile terminal testing, such as TRP [97] and also for the new parameters applied with advanced multi-antenna systems, such as capacity and diversity gain [98]. Furthermore, methods for creating non-isotropic fading environments in reverberation chambers have been presented [99]-[101]. Nonetheless, accurate control of the spatial and temporal effects of radio channels is difficult with the reverberation-chamber approach.

6.3.2 Synthesis with probe arrays

A different approach to radio channel environment synthesis is to employ multi-probe configurations to synthesize desired field distributions in the test zone. This type of a system, also called a spatial fading emulator (SFE), is more complex by structure but allows more control over the radio channel parameters, because the signals radiated by the probes can be controlled individually. Such systems have been presented for the 2-D case, where the probes are located on a horizontal circle surrounding the DUT [102]-[104]. These configurations allow for the control of the azimuthal distribution of the incoming waves in the test zone.

The concept can be easily extended to the full 3-D case, where the probes are distributed on a spherical surface [105]. Hence, the elevational distribution can be controlled, as well. Fig. 7 shows an example of such a setup, where the DUT is in the middle surrounded by a large number of probes. By feeding the probes with appropriate signals, different field distributions can be created in the vicinity of the DUT. In order to synthesize arbitrary field distributions, an infinite number of probes are, in theory, required. However, by formulating the problem in the context of the spherical-wave theory, the well-known cut-off property of the spherical wave functions (Chapter 2) can be utilized here, as well. The high-order modes near the coordinate system origin (test zone) have very small amplitudes, and can be neglected without producing large errors in the synthesis [106] [107].

The required number of probes is thus determined by the desired size of the test zone, which must be large enough to enclose the DUT. By determining the radius of the minimum sphere enclosing the DUT, the truncation number N can be determined using Eq. (2.4). The number of spherical modes required for the synthesis will then be

$$J = 2N(N + 2). \quad (6.4)$$

For exact reproduction of these modes, the number of probes should be larger than or equal to J . It is shown in [VI] that good statistical results can be obtained for parameters like the channel capacity with truncations numbers smaller than that given by Eq. (2.4). This is important since it allows reduction of the number of probes.

The multi-probe synthesis method is very versatile. It allows, for example, reproduction of any measured radio channel environment regardless of the azimuthal or elevational distribution of the angles of arrival of the multi-path components. Furthermore, by using advanced channel emulator hardware, signals with the desired Doppler shifts, delays, etc. can be produced [108]. For the 2-D case, performance of MIMO systems measured with a SFE has been compared to measurements in actual radio channel environment and good agreement between the results has been demonstrated [109].

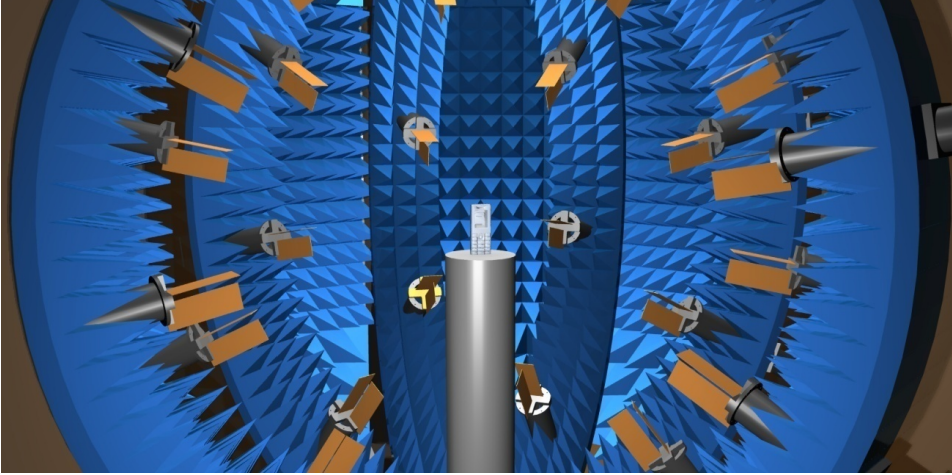


Fig. 7. Illustration of a multi-probe setup for synthesizing electromagnetic fields in the vicinity of the DUT (i.e., the test zone in the middle of the sphere).

6.4 Contributions of this thesis

In [VI], the aspects of electromagnetic theory relevant for full 3-D radio channel environment synthesis are discussed. It is shown, how the required probe excitations can be determined from the desired radio channel model in the context of the spherical wave theory by two different approaches. In the analytical approach, the test zone fields created by each probe are calculated from the known locations and radiation characteristics of the probes. This technique does not account for the signal reflections in the measurement chamber. In the measurement-based approach, the test zone fields created by each probe are measured with a known reference antenna, as discussed in [I].

This technique compensates for the signal reflections in the chamber and does not require prior knowledge of the probe characteristics or locations. The presented synthesis method is not limited to far-field scenarios, but near-field effects can also be produced, if needed.

Simulations are performed in [VI], where a mobile terminal antenna model with two radiating elements is placed in the test zone and the signal received by each element in the synthesized radio channel environment is calculated. Both the DUT and the radio channel environment models are based on measured data. In this paper, for the first time the relations between the number of probes and the errors in the measured channel capacity are studied and presented. The channel capacity is one of the candidates for the performance parameter in MIMO-OTA testing (Sec. 6.1.3). The effect of measurement noise on the uncertainty of the received signal is also studied.

The results of [VI] shed light on some of the most relevant, current research questions on MIMO-OTA testing that are of interest in the industry. These include the characteristics of the probe array (number, type, and locations of the probes), the maximum size of the DUT, the evaluation of the measurement uncertainty, and the calibration of the measurement system [110]. It is shown that a small number of probes may be sufficient for testing mobile terminals of typical size, depending on which performance parameter is of interest. With a fixed number of probes, statistical distributions of parameters can be measured with good accuracy for DUTs of larger size than that given by the conventional criterion for the test zone size.

7 Summary of publications

In publications [I] and [II], a new method was presented for compensating the effect of signal reflections in the antenna measurements. The method is a modification of the test zone field compensation technique, but unlike the original, is not iterative. Therefore, it can be applied in highly reflective environments. Furthermore, it can also be applied with irregular measurement grids. The functionality of the method was demonstrated through measurements in a normal laboratory room with lots of reflective surfaces, and also separately with a multi-probe system. Although it was tested in such a scenario, where the reflected fields were of the order of -5 to -10 dB compared to the LOS signal, the developed method is, in theory, able to correct the effect of all interfering signals of constant nature, regardless of their amplitude.

In publication [II], it was shown how the modified test zone field compensation method can be applied for calibrating a multi-probe antenna measurement system. Comparisons with the traditional S_{21} cable calibration method were presented, using a measurement with a high-accuracy spherical near-field range as the reference. In these tests, similar accuracy was obtained with the two calibration methods. The new method has, however, the advantage that it includes the effects of the environment and the probes in the calibration. It is, therefore, a more extensive calibration method, and its performance is dependent on the accuracy of the TZF measurement.

Publications [III] and [IV] dealt with improvements of the multi-probe system presented in [46]. In [III], a phase-retrieval capability was added to this system, whereby the complex radiated field of the DUT can be determined from amplitude-only measurements. This enables complex field measurements for active DUTs where VNA measurements with feed cables cannot be performed, and thus also the minimization of the required number of measurement points [49]. The performance of the phase-retrieval functionality was examined by comparisons with reference measurements by another measurement system and good agreement was found. In [IV], the frequency range and measurement speed of the system were enhanced and the measurement accuracy studied over a wide frequency range. In particular, the limitations set by the small number of measurement points (64) were examined with test measurements against an external reference. It was found that for a mobile terminal of typical size, the results are reliable up to 2 GHz. Also, the accuracy of the phase-retrieval network was tested over a wide frequency range and the cumulative distribution of the errors was presented.

In publication [V], test person measurements were carried out in the GSM900 and GSM1800 bands with an active mobile terminal. Two different measurement systems were employed, a multi-probe system and a single-probe system with a movable probe. The number of test persons was 13 in the multi-probe measurements and 3 in the single-probe measurements. By these measurements, the cause of the observed large variation

in the BL between different individuals was studied. It was found that the individual grip and hand position are the main causes of the large variations, as the variance is decreased sharply when all test persons use a similar grip. The mean body losses within the group were found to be 9.2 dB (GSM900) and 6.2 dB (GSM1800), when the test persons were allowed to hold the phone in a freely-selected way. The separate contributions of the head and the hand to the total BL were also studied. In the GSM900 band, the head caused on average a larger loss than the hand (5.4 dB vs. 4.1 dB), but in the GSM1800 band the situation was the opposite (2.0 dB vs. 3.2 dB). The head loss results were also compared to measurement results with a head phantom and it was found that the phantom is a good representation of the average human head, with losses measured at 5.8 dB (GSM900) and 1.5 dB (GSM1800).

In publication [VI], the synthesis of arbitrary radio channels in laboratory conditions for OTA testing of multi-antenna systems was investigated. A synthesis method based on the spherical-wave theory was presented and its accuracy studied through simulations. Any types of probes can be applied with the presented method and if the TZF calibration is used, it is not necessary to know their radiation characteristics beforehand. By the presented method, near-field effects can be also generated in the test zone, if required. The errors in the measured signal and channel capacity with respect to the number of probes in the system were investigated, using a two-port mobile terminal antenna model as the DUT. The effect of noise in the probe excitations was also considered. It was shown that good results for mobile terminals of typical size can be obtained with a relatively small number of probes, especially for statistical parameters like the distribution of the channel capacity. The minimization of the number of probes is an important point because it reduces the system complexity and cost.

8 Conclusions

In this work, contributions have been made in several areas relating to the testing of the radio performance of mobile terminal antenna systems. The importance of such testing is increasing due to the now ubiquitous mobile communications systems. Constantly, new ways are being devised to increase the data rates and the capacity of the mobile networks in a spectrum-efficient manner. Radio performance tests of the user equipment are critical in this development.

The topics explored in this thesis were the measurement of traditional antenna parameters, the user effect, and the interaction between the dynamic radio channel environment and the mobile terminal. The last of these questions has become crucial with the new multi-antenna technology, which is applied to take advantage of the radio channel characteristics in order to improve the link performance of the communications system. The selection of performance metrics that should be applied and standardized for OTA testing of multi-antenna systems is not an easy task and is under active debate [111] [112]. Irrespective of the outcome of this debate, it is likely that the testing will require some sort of reproduction of radio channel environments in laboratory conditions. One such reproduction method was developed and investigated in this work.

Despite the ongoing development of new performance parameters and test methods, traditional antenna testing, i.e., measurement of radiation patterns and efficiencies will be required for a long time yet. They are key parameters in the development of new antenna elements, and measurements of them are essential in the antenna design process, even if the ultimate performance parameters for the complete mobile terminal antenna system are something else. Therefore, the ways developed in this work to increase the measurement speed and reduce the costs of the measurement of small antennas are relevant as well.

The effect of the user's body on the mobile terminal antenna performance is an important question because mobile terminals are nearly always used in the proximity of the body. This effect needs to be studied with both aforementioned testing methods, i.e., the traditional antenna measurements and the measurements under realistic radio channel conditions. Traditional antenna measurements with phantoms or test persons give insight to the mechanisms through which the body affects the antenna radiation, and similar measurements under radio channel environments show the ultimate effects the body has on the mobile terminal radio performance. In this work, the user effect was studied through traditional antenna measurements with live test persons, using a multi-probe system. New information was obtained on how the body influences the performance of the mobile terminal antenna.

Future tasks in the standardization of mobile terminal OTA testing include the selection of the figures of merit and the selection of the applicable test method(s) for multi-antenna terminals. Also, how to evaluate the impact of the user's hand in the mobile terminal antenna performance is an important question. Further research in the area is indicated before these issues can be settled.

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ISBN 978-952-60-3310-5 (paper)
ISBN 978-952-60-3311-2 (electronic)
ISSN 1797-4364 (paper)
ISSN 1797-8467 (electronic)